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Review of Literatures on Modeling and Experimental Studies of Combined Darrieus – Savonius Wind Machine

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Abstract

Wind is one of the promising available alternative sources of energy to meet the growing global energy demand which is predicated by the exponential growth in world population. This has prompted reinvigorated research efforts towards improving the performances of Wind Energy Conversion systems. In this regard, quite a number of successful investigations have been carried out and still on going to improve and optimize performance of Vertical Axis Wind Turbines (VAWTs). However, there still exist some knowledge gaps in the aerodynamics and performance of the VAWTs. This work is a review of the previous investigations on the performance improvement and optimization of VAWTs. It is shown from the review that there is a wide knowledge gap on the effect of Savonius rotor on the performance of hybridized rotor after starting while rotating at higher rotor speeds. Also, the influence of varying geometrical parameters on other adjacent ones has not been systematically investigated in the previous studies. Largely, the investigators did not explore the simultaneous use of both experimental and numerical methods in their investigations. The findings from the review reiterate the need for considering a means of disengaging Savonius rotor from the combined rotor after starting. It was shown that two bladed Savonius rotor is more efficient than three and four bladed rotors; hence, the need for its consideration in future improvement works on the combined rotors. The rotors with end plates give higher efficiency than those without end plates. Double staged rotors have higher performance than single staged rotor. The rotors without overlap ratios are better in operation than those with overlap. It was also revealed that the power coefficient increases with the rise in aspect ratio. Three Straight bladed Darrieus rotor is observed to be more efficient than the traditional egg – beater shaped, hence, the need for its adoption in future performance improvement works. Savonius rotor without overlap ratio should be placed below Darrieus rotor for optimum efficiency as revealed from literatures. For future improvement and optimization works, method of disengaging the Savonius rotor from Darrieus after starting at certain wind and rotor speed is recommended. In order to ensure a balanced model for more accurate data, Method of fabrication and machining should consider the use of CNC machines. To effectively study the influence of varying geometric parameters on others, there is the need to conduct orthogonal analysis. The study has to combine both experimental and numerical methods of investigation as well as ANOVAL tests of the experimental results.

Keywords: Vertical Axis Wind Turbines, Performance optimization, combined Darrieus –Savonius rotor,

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1. INTRODUCTION

1.1 BACKGROUND OF THE STUDY

In recent years, the entire world is experiencing serious global warming and climatic change with related environmental problems arising from over dependency on fossil fuel energy resources in meeting the ever increasing energy demand due to exponential growth in population. This ugly trend has prompted the recent reinvigorated interest and researches on renewable energy resources, such as, solar, wind, hydro, geothermal bio fuel, tidal etc. These concerns have led to the formulation of policies by the stakeholders in wind industry. One of such policies was that of the UK government, under the Kyoto Protocol, in which a target was set for the renewable energy generation of 10% of UK energy consumption by 2010 (Okeoghene, 2013). This policy, according to UK Energy statistical report of 2014, contributed to the achievement of 40% of UK's renewable energy generation from wind in 2010 (Okeoghene, 2013).

Similarly, in line with the ongoing global mitigation effort towards eliminating causes of Green House Gases (GHG) emission, such as oxides of carbon, Nitrogen and Sulphur, and their attendant negative environmental effects, the Federal Government of Nigeria has through the Ministry of Power and Steel, formulated what it referred to as"The policy Guidelines on Renewable Energy Electricity" (Renewable Electricity Policy Guidelines December, 2006). The guideline sets out federal government's vision, policies and objectives in promoting renewable energy in the power sector.

In Nigeria, the potential of wind energy in the nation's energy mix have been investigated by some researchers. According to the result of one of such investigations, the annual wind speeds and power flux were determined to vary from 1.5 to 4.1 m/s and 22.5 W/m^2 (Adekoya and Adewale.1992). The investigation asserted that the potential uses of wind energy in the country are for electricity generation and water pumping in rural areas.

Harnessing energy from wind, will not only reduce environmental pollution through minimising carbon emission into the atmosphere, but can also provide adequate and affordable energy which can aid in the eradication of poverty, thereby raising the living standards (Okeoghene 2013). This also, will encourage job creation through researches into the improvement, developments, operations and maintenance of wind machines (Okeoghene2013)

In a bid to harness kinetic energy of the wind for mechanical and electrical applications, two popular known converting systems are often employed, namely: Horizontal Axis Wind Turbines (HAWTs) and Vertical Axis Wind Turbines (VAWTs). A schematic diagram of the HAWT and VAWT are as respectively shown below.

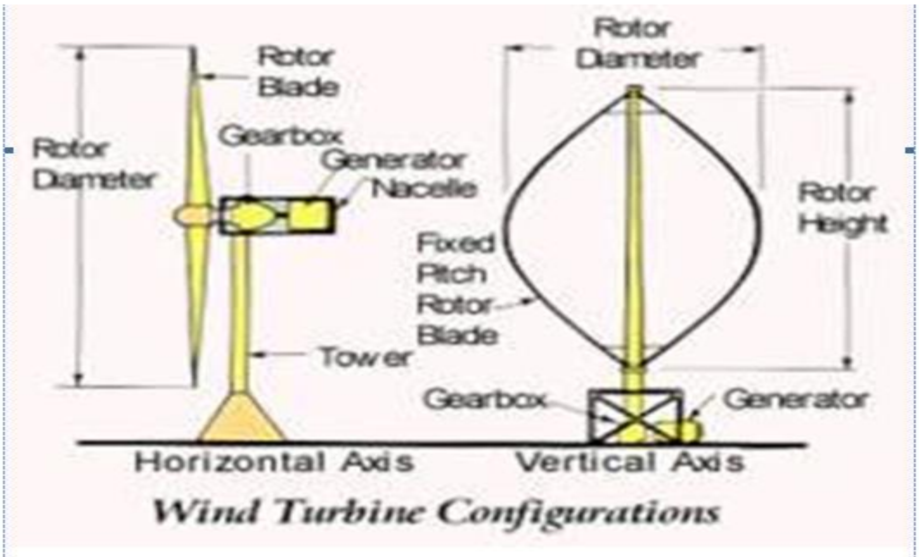

Figure A1: Schematic Diagram of Horizontal and Vertical Axis Wind Turbine Configurations (source: http://int.search.myway.com/assets/common/spinner.gif)

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Advantages of VAWT

VAWTs are mostly viable for applications in low wind speed regimes of about 3-5m/s where HAWTs are highly uneconomical. VAWTs emit less acoustics in operation compared to HAWTs, hence, their suitability for top roof mounting turbine applications in urban and rural settlements. In addition, VAWT rotors do not require any yawing mechanism that brings the plane of rotation of the blades to wind direction as required in case of HAWT, hence, the renewed interest and reinvigorated research efforts on the performance improvement of their rotors.

Types of VAWTs

VAWTs are of two basic types depending on their rotor configurations; Savonius and Darrieus rotors as respectively shown below

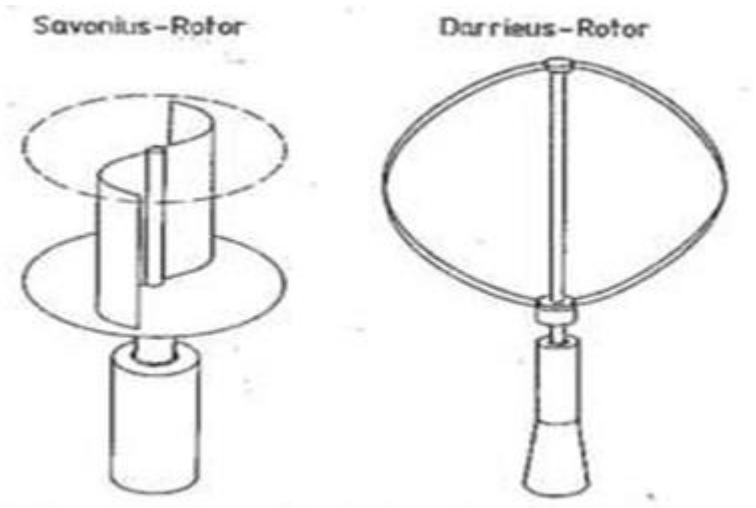

Figure 2: Types of VAWTs

Savonius rotors are drag - based, self-starting due to inherit high torque deliverable at low speeds. They exhibit low Tip Speed Ratio (TSR) at high wind speeds and are often employed for mechanical operations, such as, milling and water pumping operations.

Darrieus blades are lift based type of VAWTs and due to the profile of their blades, they exhibits higher TSR than Savonius but lesser torque and as such, lacks self-starting capability in low wind speeds. As a result of their high TSR potential, they are often employed for electrical generation applications. One of the most popular ways of overcoming the shortfalls of the two types of VAWTs rotors (Darrieus and Savonius), is by combining the two rotors in one axis as shown below.

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Figure 3: Combined Darrieus – Savonius Rotor

(Source; https://s.yimg.com/pv/static/img/viewer_sprite-201505202039.png)

Accessed on 3rd June, 2017:2.00 p.m.

The attempt is to provide a more efficient VAWT that exhibits high torque required for self-starting capability and TSR for electrical generations. In this regard, several configurations of the combined rotors with varied shapes and geometry have been investigated with considerable performance improvements.

Notably, the structure of a wind rotor is constructed by multiple geometric shapes or structural parameters such blade profile, number of blades, height of blades, ratio of height of blades (hybridised rotors), rotor configuration, pitch, chord length, blade diameter etc. These simply imply that there is a combined action of the parameters on performance of the wind rotor. Change of a parameter has influence on other adjacent parameters; thus, there are always interactions among them.

Revelations from relevant literatures on previous investigations to solve the inherent starting problem of Darrieus wind turbines by its combination with Savonius rotor have shown that there still exist knowledge gaps in the effects of Savonius rotor on the aerodynamics and performance of the combined Darrieus – Savonius rotor after starting while running at higher rotor and wind speeds**.**

PROBLEM STATEMENT

As did Abubakar and Garba (2015**);** the effects of height ratios of the Savonius and Darrieus rotors on the performance of the combined model were investigated. Though, the experimentally based investigation was able to show the interactions of the heights with the performance of the hybridised rotors, however, the effects of the Savonius rotor after starting was not shown. Also, the experimental investigation results needed validation using Numerical methods for the models performance optimisation. It was also shown that to obtain a high level precision of the models which is important for a more accurate and reliable experimental result, method of fabrication and machining should consider using Computer Numerically Controlled machines.

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2. THEORETICAL FUNDAMENTALS

2.1 Wind Speed and Power

2.1.1 Wind

Wind is a mass of air in motion which occurs due to uneven heating of the atmosphere by the sun, the irregularities of the earth's surface, and the rotation of the earth.

Wind resource assessment provides the necessary information required in determining the feasibility of installing a typical wind turbine as a viable source of energy at a location. A detailed assessment will provide wind pattern, data and Mathematical formulation which are useful in making decisions of deployment of wind turbine in a particular geographical location

2.1.2 Wind Speed & Power

Wind speed, or wind flow velocity, is a fundamental atmospheric quantity caused by movement of mass of air from a region of high pressure to low pressure, usually due to changes in temperature

Wind power is proportional to the cubic wind speed; hence, it is crucial to have detailed knowledge of the site-specific wind speed characteristics. Small errors in estimation of wind speed can have large effects on the energy yield, poor choices of turbine and site. An average wind speed is not sufficient; Site-specific wind characteristics which are peculiar to wind turbines include: mean wind speed, wind speed distribution : diurnal, seasonal, annual patterns turbulence: short-term and long-term fluctuations, distribution of wind direction and wind shear (profile). Due to this stochastic characteristic of wind, information about wind speeds variation over time is important in designing and optimisation of wind turbines. It is important to investors in estimating their income from investments. Wind speed and direction is often influenced by topography of an area.

Olagbegi, Kwasi-Effah and Ugbi (2014**),** investigated the effect of wind speed and direction on the performance output of a wind electric generator using the TPS-3730 wind energy training system available in the Department of Mechanical Engineering Laboratory, University of Benin. The study showed that the output voltage of the wind electric generator greatly depends on the wind speed and degree of wind turbulence. The Authors asserted that site wind characteristics need to be considered in designing and installing a wind turbine or wind electric generator in any given location.

Wind speed distribution at a site is important in determining the average power, annual energy yield, payback period and economic viability of installing wind turbine. The most commonly used distribution methods are Weibull and Rayleigh distribution functions. These statistical tools describe how often a wind speed class is observed at a location. A typical graphical representation of variation of wind turbine power with speed is as shown below.

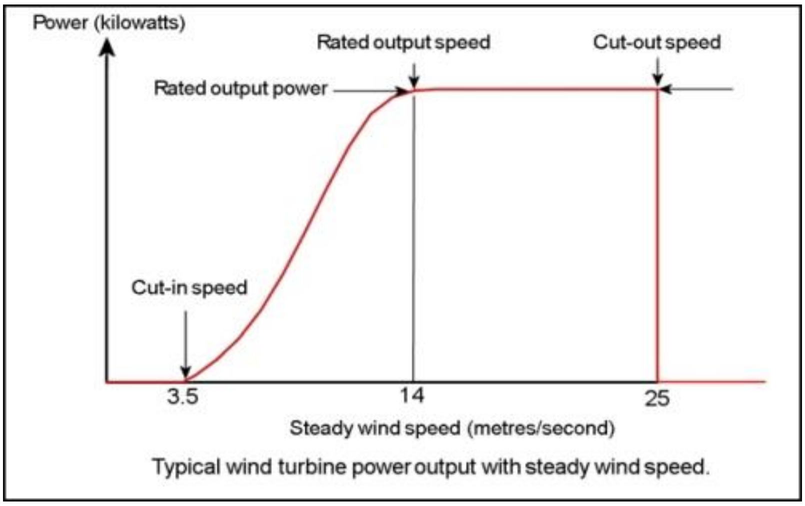

Figure B: Variation of Wind Turbine Power output With Wind Speed

(Source:http://www.wind-power-program.com/turbine_characteristics.htm)

Accessed on 10rd November, 2017:4.00 p.m

The variation of wind speed at a constant rate over time is used in designing turbines to have three classical power output speed ratings; cut – in, rated and cut –out speeds.

i. Cut-in speed

At very low wind speeds, there is insufficient torque exerted by the wind on the turbine blades to make them rotate. However, as the speed increases, the wind turbine will begin to rotate and generate electrical power. The speed at which the turbine first starts to rotate and generate power is called the ***cut-in speed*** and is typically between 3 and 4 metres per second.

ii. Rated output power and rate output wind speed.

As the wind speed rises above the cut-in speed, the level of electrical output power rises rapidly as shown above. However, typically, somewhere between 12 and 17 metres per second, the electric generator power output reaches the rated limit called the ***rated power output***. The wind speed at which this is attained is called the ***rated output wind speed.*** At higher wind speeds, the design of the turbine is arranged to limit the power to this maximum level and there is no further rise in the output power.

iii. Cut-out speed.

As the wind speed increases above the rate output wind speed, the forces on the turbine structure continue to rise and, at some point, there is a risk of damage to the rotor. As a result, a braking system is employed to bring the rotor to a standstill. This is called the ***cut-out speed*** and is usually around 25 m/s

The terms wind energy or wind power are used interchangeably and refer to the energy possessed by wind by the virtue of its motion and describes the process by which wind is used to generate mechanical power or electricity. Wind Power is a function of amount of air (volume), speed of air (velocity), mass of air (density), flowing through an area of interest (flux) as given by the equation below:

$$\text{Kinetic Energy} = \frac{1}{2}\text{mV}^2 \qquad 1$$

where:

m is the mass of air in motion

V is the velocity of air in motion

Power is the kinetic energy per unit volume

$$P = \frac{1}{2}\dot{m}V^2 \qquad 2$$

Where:

$$\dot{m} = \frac{dm}{dt}$$

$$\frac{dm}{dt} = \rho AV \qquad 3$$

Thus;

$$P = \frac{1}{2}\rho AV^3 \qquad 4$$

Where P is the wind power in Watts

ρ is the air density in kg/m^3

A is the blade swept area in m^2

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And V is the wind speed in m/s

2.1.2 Power Coefficient and Bertz Limit

It is impracticable unless the whole blade has to come to a halt; to extract the whole energy in the wind by any wind turbine.

Power Coefficient, Cp, is the ratio of power extracted by the turbine (P_T) to the total contained in the wind resource (P_W)

$$C_P = {}^{P_T}/_{P_W} \quad 5$$

$$P_T = \frac{1}{2}\rho A V^3 C_P \quad 6$$

The maximum extractable energy C_P from the wind by any wind machine is given by Bertz otherwise known as Bertz limit (16/17).

Thus:

$$P_T = 0.35\,\frac{1}{2}\rho A V^3 \quad 7$$

2.2 Kinematics of VAWTs

Bodies in a fluid flow experience fluid-dynamic forces and moments. Such forces and moments are directly related to the characteristics of vehicles (such as speed, acceleration, stability and fuel efficiency). These are also directly related to the performance of fluidic energy devices, such as wind turbines and marine turbines. Force coefficients are often useful to define non-dimensional “force coefficients” for the lift (F_L) and drag (F_D) forces which enables comparative aerodynamic performance at different scale speeds.

Drag and lift coefficients are usually defined as:

$$C_D = \frac{F_D}{\frac{1}{2}\rho V^2 A} \quad 8$$

$$C_L = \frac{F_L}{\frac{1}{2}\rho V^2 A} \quad 9$$

Where:

A = reference area, which can be a frontal projected area of a body

V = wind speed

ρ = air density

2.3 Vertical Axis Wind Turbine Design and Performance Parameters

The most significant of the VAWTs geometric and performance parameters involved in the design and performance testing of the VAWTs are as defined below:

2.3.1 Swept Area:

The swept area is the section of air that encloses the turbine in its movement and is given by:

$$A_S = HD \quad 10$$

2.3.2 Co – efficient of Power

The ratio of power in the wind to the extracted power by the turbine is defined as the power coefficient and calculated using the relation given below.

$$C_P = \frac{\text{Mechanical power extracted by the wind}}{\text{Available power in the wind defined by the swept area of turbine}} \qquad 11$$

2.3.3 Tip speed ratio:

It is defined as the ratio between the tangential speed at blade tip and the actual wind speed

$$\lambda = \frac{\text{Tangential speed at blade tip}}{\text{Actual wind speed}} \qquad 12$$

2.3.4 Number of blades:

The number of blades has a direct effect in the smoothness of rotor operation. From various references it is concluded that two or three blades are more suitable for vertical axis wind turbine.

2.3.5 Solidity:

It is defined as the ratio between the total blade area and the projected turbine area.

2.3.6 Angle of attack:

This is the angle between the direction of wind flow and the blade chord line

2.4 Combined VAWT Design Equations

Some important relations for analytic design and performance calculation of combined Darrieus – Savonius wind turbines are as given as follows.

2.4.1 Power Output

$$P = 0.5 * \rho * V^3(A_S CP_S + A_d - A_s * CP_d) \qquad 13$$

(Parth, KapilKhatik, Ketul and, Jay, 2016)

Where,

A_S = area swept by Savonius rotor in m^2;

A_d = area swept by Darrieus rotor in m^2;

CP_S = Power coefficient of Savonius rotor;

CP_d = Power coefficient of Darrieus rotor

P = Air density in kg/m^3;

Ω = Shaft speed in rad/s;

V = wind speed in m/s

2.4.2 TSR of hybrid turbine;

$$\lambda = \omega / RV \qquad 14$$

Where,

R = Maximum rotational radius;

ω = Shaft speed in rad/s;

2.4.3 Total Torque (Q_T) for the combined model

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$Q_T = Q_S + Q_D$ 15

(Parth, KapilKhatik, Ketul and, Jay, 2016)

Where;

Q_T = torque of the combined machine;

Q_S = torque of the Savonius rotor;

Q_D = torque of the Darrieus rotor

And;

$Q_T = 12\rho A_T R R_T C Q_r$ 16

(Parth, KapilKhatik, Ketul and, Jay, 2016)

Where

$CQ_r = (CQ_S A_S D_S A_T R_T) + (CQ_D A_D R_D A_T R_T)$ 15

(Parth, KapilKhatik, Ketul and, Jay, 2016)

Where;

R_D = equatorial radius Darrieus turbine;

A_D = swept area of Darrieus turbine;

D_S = diameter of Savonius rotor;

R_T = radius of the combined machine;

A_T = swept area of the combined machine.

The power coefficient of combined machine has been evaluated as:

$CP_R = ƙCQ_r$ 17

(Parth, KapilKhatik, Ketul and, Jay, 2016)

Where;

CP_R = Power coefficient of the combined rotor

3. LITERATURE REVIEW

A great deal of investigations have been and still being conducted on the most important geometric parameters which often influence the performance of combined VAWTs such as torque, power, C_P and TSR includes: number, relative positions, and overlap as well as heights ratios of the Savonius and Darrieus blades of the combined mode. The single and combined effects of these parameters on the hybridised VAWTs must be understood, since a single parameter cannot conclusively determine how the VAWT performance and lifespan can be improved.

The approach and procedure adopted in this investigation is such that single Savonius geometric parameter of combined VAWT are modeled and tested by varying different parameters for proper understanding of the effects of such parameters varied. Thereafter, the revelations from these separate parameters tested are integrated for an overall decision regarding improvements and optimization. Review of literatures on some studies carried out on the effect of varying Savonius blade geometric parameters on the combined VAWTs' performance are presented in the following subsections.

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3.1 EFFECT OF SAVONIUS BLADE GEOMETRIC PROPERTIES ON THE COMBINED DARRIEUS - SAVONIUS MODEL

Gupta, Biswas and Sharma (2017), carried out Comparative study of a three-bucket Savonius rotor with a combined three-bucket Savonius–three-bladed Darrieus rotor. The Savonius–Darrieus rotor was a combination of three-bucket Savonius and three-bladed Darrieus rotors with the Savonius placed on top of the Darrieus rotor. The overlap variation was made in the upper part, i.e. the Savonius rotor only. These were tested in a subsonic wind tunnel. The various parameters namely, power coefficients and torque coefficients were calculated for both overlap and without overlap conditions. It was observed that there is a decrease in power coefficient with increase in overlap ratio. The maximum power coefficient of 51% was obtained at no overlap condition. However, while comparing the power coefficients (C_p) for simple Savonius-rotor with that of the combined configuration of Savonius–Darrieus rotor, it is observed that there is a definite improvement in the power coefficient for the combined Savonius–Darrieus rotor without overlap condition. Combined rotor without overlap condition provided an efficiency of 0.51, which is higher than the efficiency of the Savonius rotor at any overlap positions under the same test conditions. The result of the investigation suggests adoption of no overlap conditions of Savonius rotor for hybridised mode.

Kaprawi, Dyos, and Dewi (2018), investigated the effect of rotor radius on the performance of Combined Darrieus-Savonius Wind Turbine. The combined model of Darrieus and Savonius blades was tested in wind tunnel test section with constant wind velocity and its performance was assessed in terms of power and torque coefficients. The effect of the radii of the Savonius and Darrieus rotors on the performance of the turbine was studied. The results show that there is a significant influence on the turbine performance with varied rotor radii. The dimensionless radius is called RL, which is the ratio of the Savonius rotor to the Darrieus rotor. It was shown that that the variation in Darrieus rotor radius in a combined turbine has an important effect on the turbine performance. The higher the RL, the lower the power coefficient, and the higher the torque coefficient. Similarly, in case of increasing the Savonius rotor radius, the power coefficient is lower but torque coefficient is higher.

Zheng, Li1, Teng1, Hu1, Tian1 and Zhao1 (2016), investigated the influence of number of blades on the performance of drag based VAWTs using ANSYS numerical simulation method with 3-bladed, 5-bladed and 6-bladed Savonius rotors at 8m/s wind speed. The result showed increased in power efficiency with increase in number of blades; 20.44%, 24.30% and 26.81% respectively. However, there is a recorded decrease in rotor speed with increase in number of blades with corresponding increase in torque; 20 rpm, 18 rpm and 17 rpm for 3, 5 and 6 blades, respectively. This suggests more number of blades of the Savonius will assist more in starting combined Darrieus – Savonius Wind machine. The results reveals that for combining Savonius and Darrieus rotors, the application in question will determine ratio of number of blades of the rotors. The study suggests that when designing for Mechanical applications, more number of Savonius blades is recommended. On the other hand, when designing for electrical applications, fewer number of Savonius blade will suffice. The study did not however, consider the effects of the Savonius rotor on the combined models after starting while rotating at higher wind speeds.

Similarly, Mohammed (2013**),** carried out comparative experimental performance investigations between two and three blades Savonius wind turbine. It was observed from the measured and calculated results that the two bladed Savonius wind turbine is more efficient, it has higher power coefficient under the same test condition than that of three blades Savonius wind turbine. The Author asserted that increasing the number of blades increased the drag surfaces against the wind air flow and caused to increase the reverse torque and leads to decrease the net torque working on the blades of Savonius wind turbine. Though to some extent, the results of this study seemingly corroborated the claims of the above, there is a disparity on the power efficiency with number of blades. From the equation relating power, speed and torque ($P = 2\Pi NT$), it is shown that when more speed is desired, torque is compromised. Also, more speed implies more shaft power, hence, two bladed Savonius rotor is recommended for combined Darrieus – Savonius models.

Mahmud, El-Haroun, Wahba and Nasef (2010) developed sets of Savonius rotors. These were made up of; two, three and four blades; with single and double stages; with end plates and without end plates; with aspect ratios of 0.5, 1, 2, 4 and 5 and with different overlap ratios from 0 to 0.35, respectively. The experimental models were investigated with a view to determine the optimum geometries of Savonius turbine. It was shown that; the two bladed rotors are more efficient than three and four bladed rotors. The rotor with end plates gives higher efficiency than those without end plates. Double stages rotors have higher performance than single stage rotor. The rotors without overlap ratios performed better in operation than those with overlap. It was also shown that the power coefficient increases with corresponding increase in aspect ratio. The respective relationships between the investigated variables with power outputs are represented as respectively in figure 3 below.

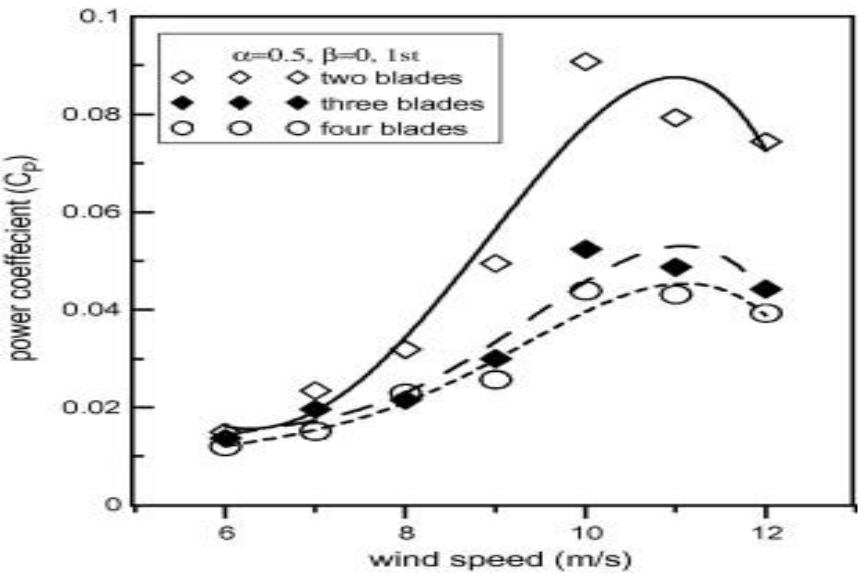

Figure 3: power Coefficient variation with speed (source: Mahmud, El-Haroun, Wahba and Nasef (2010)

The result of their investigation corroborated that of Zheng, Li1, Teng1, Hu1, Tian1 and Zhao1 (2016) above in terms of efficiency. It provided important performance data sets about Savonius rotor, however, it is experimental based which requires numerical analysis methods to make the claims more valid and reliable.

Recently, significant performance improvement on Savonius rotor have looked beyond variations of the geometric parameters of conventional s – shaped rotor to include modifying rotor shapes and attachments such as fish – ridged shaped, helical or twisted shape etc. Some designs included a guide while some studies consider an array of the Savonius rotor in a wind farm. Review of some of such performance enhancement investigations reveals higher C_P than the traditional S – Savonius rotors. Fish Ridged Savonius Rotor with Straight Bladed H – Darrieus Rotor are most preferred for improvement and optimisation due to their inherent efficiency and simplicity in design and ease of fabrication.

Danao, Ning and Robert (2012), studied the effects of aerofoil thickness and camber on the performance of a 5Kw scale VAWT using Computational Fluid Dynamic (CFD) methods. The investigation revealed that thinner aerofoils performed better than the thicker aerofoils due to the higher pressure coefficient experienced by the thinner aerofoils. More energy is extracted by the thinner aerofoils than the thicker blades. It was also shown that slightly cambered aerofoils such as LS0421, can improve overall performance of the VAWT better than a highly cambered one.

Beri and Yao (2011), investigated self-starting capability of VAWT with emphasis on cambered blades and stated that cambered blades can provide the potentials for the self-starting of the VAWT recording high CP at optimum wind speeds. The result of this study suggests adoption of cambered blades of Darrieus rotor in the combined models.

Okeoghene (2013), investigated the Influence of Blade Chord on the Aerodynamics and Performance of Vertical Axis Wind Turbines using Experimental and Computational Fluid Dynamic methods. It was revealed from the investigation that the CP of VAWTs is dependent on the blade chord (solidity), wind speed and Reynolds numbers. The rotor with Chord length of = 0.03m ($\sigma = 0.26$) VAWT attained lower CP than that with Chord length of 0.04m ($\sigma = 0.34$) VAWT, conducted at the lowest and highest wind speeds test.

Gupta, Sharma and Biswas (2008**),** developed a three bucket Savonius rotor and combined it with the central shaft of a traditional Darrieus. Some impressive results were obtained from the tests of various geometries of the Savonius rotors. It was shown that by allowing a 16% air gap between the buckets of the Savonius rotor attached to the Darrieus shaft, Cp of 0.3403 was seen along with a tip speed ratio of 0.305. However, by removing the air gap between the buckets of the Savonius rotor and combining this with a Darrieus rotor, an incredible Cp of 0.51 was realized with a tip speed ratio of 0.62.

Adamu, Sani, Adam, Hussaini, Olumuko, Olojo and Ohida (2010), developed a 0.75 – 1Kw VAWTs at Hydraulic Equipment Development Institute Kumbotso, Kano. A two bladed Savonius rotor was placed between three bladed NACA4415 Darrieus aerofoil blades and mounted on a roof top. The effect of permanent placement of the Savonius rotor at the central position without means of disengagement after starting on the performance of the combined rotors was not shown. It was recommended by the

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investigators that further improvement efforts on the model VAWTs should consider the use of fibre materials which are more rigid and lighter in weight than the wooden material.

Similarly, Jamila and Adamu (2011) developed and carried out performance testing of some selected aerofoil blades: NACA4415, 2412 and 0015 casted with fibre materials. (Polyester and resin). NACA0015 was used as a case study and the result showed increase in lift forces with corresponding variation of angle of attack and at maximum at 17.7 degrees. Similar observation was also made of the drag forces, hence, the consideration for adoption of NACA00015 Darrieus aerofoil fixed at 17.7 degrees is highly recommended for future improvement works.

Abubakar and Garba (2014), carried out comparative performance analysis on three wind tunnel scaled models of combined Darrieus – Savonius Wind machines. The hybridized models consist of 1:1, 1:2 and 2:1 height ratios of Darrieus – Savonius rotors. The models were tested in a subsonic wind tunnel at Faculty of Engineering, Bayero University Kano. Analysis Of Variance (ANOVA) test was conducted on the experimental data using SAS package. The result showed that; Model 2:1 exhibits better self-starting capability at 3.4 m/s with highest Tip Speed Ratio (TSR) suitable for electrical generations in low wind speed regimes. Model 1: 1 started at 3.5 m/s and have higher shaft power and torque suitable for mechanical applications in low wind speed. Though the result of the investigation proved quite impressive showing the effects of blade height on the performance of the hybridised rotors, it did not determine the effect of Savonius rotor on the performance of the model at other wind speeds after starting. It ought to have incorporated a mechanism for disengaging the Savonius rotor after starting and examine its performance. Also, the study did not seek to specify the optimum ratios that will give minimum possible self-starting wind speed, maximum TSR and shaft powers. The investigation like other similar investigation did not harmonize and integrate the effect of other findings on performance improvement on VAWTs for possible optimization of the combined rotor efficiency.

Yan (2019), observed that although the improvement of starting performance by adding Savonius rotor is obvious, the power performance at high rotational speed is greatly affected. The reason is mainly because the Savonius rotor will be turned into a load when its tip-speed ratio becomes larger than unit. Therefore, the combination factors should be deeply researched such as their rotor diameter, combine angle, aspect ratio, etc.

Seng, Misaran and Wan Ibrahim (2020), developed combined Savonius and Darrieus rotors. Comparative performance testing of the model was carried out with a standalone Darrieus turbine with +3 degree pitch angle. The result showed promising result in lowering the self-start speed of the Darrieus turbine. It was observed the hybridised model started to rotate at lower wind speed (about 1.8 m/s) while the standalone Darrieus turbine started rotating at wind speeds more than 3.0 m/s.

4. RESULTS OF THE REVIEW

4.1 KNOWLEDGE GAPS DISCOVERED

In general, the observed knowledge gaps from the review are as enumerated as follows.

i. In most cases, in varying the geometric parameters for performance improvements one geometric parameter is often considered at a time without due consideration of the effects of its influence on the adjacent parameters and on the performance.
ii. Some of the respective optimum values of the geometric parameters have not been determined. For example the optimum height ratios of combined Darrieus - Savonius rotor that will give optimum performance in terms self-starting, C_p and efficiency have not been shown in the previous works.
iii. The effect of Savonius rotor on combined Darrieus Savonius rotor after starting when turbine is operating at higher wind speeds and Reynolds numbers have not been shown in the previous investigations.
iv. Some of the results of the investigations are quite impressive but considered only one method of investigation. Numerical, experimental and physical models ought to have been created and tested to see the corroboration of their results to make claims valid and reliable or else suggest further improvements.
v. There is none of the investigations that integrated the geometric parameters in one combined Darrieus - Savonius rotor to show the optimum model

4.2 DISCUSSION ON THE FINDINGS

From the review of relevant publications on performance improvements and optimization of combined Darrieus Savonius wind machine, it is shown that the effect of Savonius rotor on the hybridized rotor has not been shown. Also, the effect of varying geometrical parameters on other adjacent ones has not been thorough fully investigated by previous studies. Methods of experimentation in most cases did not considered simultaneous use of both experimental and numerical methods. In fabricating the experimental models as the case with some investigators, CNC machines were not employed in the process.

4.3 JUSTIFICATION FOR THE STUDY

From the review of relevant literatures on performance improvement and optimisation of VAWTs, some important knowledge gaps and shortfalls are noticed. A very significant shortfall that has been observed with the previous studies is lack of integration of geometric parameters by the investigators. The influence of geometric parameters as shown by different investigators, when coordinated and integrated in to one design needs to be examined Another observation is that in all attempts to investigate the effect of combining Darrieus rotor with Savonius rotor to solve the problem of non – self-starting ability of the Darrieus lift based rotor, there is the need to examine possible negative effects of the drag based rotor on the performance of the hybridized rotor. And as such, there is the need to design and develop a mechanism for disengaging Savonius rotor from the combined system after starting. The thrust and justification of this present investigation is to focus on and fill these knowledge gaps in previous works which are very important to performance improvement and optimisation of VAWTs.

5. CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

i. The findings from the review of relevant literatures reiterate the need for considering a means of disengaging Savonius rotor from the combined rotor after starting. This is to enable comparative performance measurements of the rotors with and without Savonius rotors.

ii. It was shown that the two blades rotor is more efficient than three and four blades rotors. The rotor with end plates gives higher efficiency than those without end plates. Double stages rotor has higher performance than single stage rotor. The rotors without overlap ratios are better in operation than those with overlap. The results also showed that the power coefficient increases with the rise in aspect ratio (α).

iii. Double stage Savonius rotors are observed to be more efficient than the single stage.

iv. Three Straight bladed Darrieus rotor is observed to be more efficient than the traditional egg – beater shaped. Savonius rotor without overlap ratio should be placed below Darrieus rotor for optimum efficiency as revealed from literatures.

5.2 RECOMMENDATIONS

i. For future performance improvement works, method of disengaging the Savonius rotor from Darrieus after starting at certain wind and rotor speed is recommended.

ii. In order to ensure a balanced model for more accurate data, Method of fabrication and machining should consider the use of CNC machines.

iii. To effectively study the influence of varying one geometric parameters on adjacent ones, orthogonal analysis method need to be conducted.

iv. Further investigations on performance improvements and optimizations should consider comparatively, experimental and numerical analysis of investigation as well as ANOVA tests of the experimental results.

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